COPPER NUTRITION OF CUCUMBER (*CUCUMIS SATIVUS* L.) AS INFLUENCED BY DIFFERENT SOURCES AND RATES OF PHOSPHORUS AND DIFFERENT FERTILIZER PLACEMENTS

By

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A DISSERTATION PRESENTED TO THE GRADUATE COUNCIL OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF TABLES (Continued)

LIST OF FIGURES

Abstract of Dissertation Presented to the Graduate Council of the University of Florida in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy

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The effects of Cu rates, P rates and sources and fertilizer placements were studied with cucumbers during two years in field and greenhouse experiments. Results of the field experiments on Leon fine sandy soil showed that an increase in Cu application rates from 0 to 2.24 kg/ha increased total yields from 11.2 to 21.4 tons/ha. A further increase in Cu application rate to 8.96 kg/ha increased yield to 24.7 tons/ha. Cucumbers also responded significantly to P applications. At P rates of 0, 28, 56 and 112 kg/ha, yields were 15.8, 21.2, 20.3 and 19.9 tons/ha, respectively. An interaction between P rates and Cu rates on early yields was significant. Application of high rates of Cu with low rate of P resulted in a yield reduction. High P rates with low rate of Cu application also brought

about decreased yield. Yields were highest when Cu was applied at the rate of 8.96 kg/ha and P applied at the rate of 56 kg/ha.

Fertilizer placement interacted with Cu rate effects on early and total yields. An increase in Cu application rate from 0 to 8.96 kg/ha resulted in increased yields with both placements but yield increased 154 percent with the broadcast placement and only 82 percent with the band placement.

Total yields were significantly greater with ordinary superphosphate as the P source than with either diammonium phosphate or concentrated superphosphate. Yields were comparable with the latter two P sources.

The application of increased rates of P resulted in increased P levels in plant tissues but significantly reduced tissue Cu 30 days after planting and during the harvest stage. The application of increased rates of Cu increased the levels of tissue Cu at both growth stages but decreased tissue P concentration at the harvest stage; Cu application had no effect on tissue P level during the early growth stage.

In the greenhouse, dry matter yields of soil-grown plants increased as Cu application rates increased from 0 to 1 ppm. Also, the application of P from 0 to 30 ppm resulted in increased yields. Reduction in dry matter yield, however, was obtained with P applications higher than 30 ppm. With nutrient solution experiments, optimum

levels of Cu and P were found to be approximately 0.02 and 30 ppm, respectively. Plants grown with only the ammonium form of N produced much less growth than those supplied with only the nitrate form of N.

INTRODUCTION

Cucumbers (*Cucumis sativus* L.) are extensively grown in Florida where the crop ranks twelfth in acreage and value of vegetables grown (48). In 1971, over fourteen thousand acres were planted to cucumbers with a production value estimated at approximately eleven million dollars.

The use of copper (Cu) in the fertilizer for many crops in Florida has been shown to be essential. With watermelons, yield increases of over 1,000 percent have been obtained by application of Cu (56). There is however, a need for additional information on the use of Cu for many crops. Studies regarding Cu requirement of cucumbers have not been found.

Phosphatic fertilizers affect crop utilization of soil Cu (57, 81, 82). Under conditions where Cu is low, the application of phosphorus (P) has induced Cu deficiency resulting in reduced crop yields. Other workers have shown that the effects of P on Cu availability may be modified by the source of P (57) and fertilizer placement (59).

The objectives of this study were as follows: (1) to determine the effects of Cu on cucumber production, (2) to evaluate the effects of P rates, P sources and fertilizer placements on cucumbers, and (3) to study the nutritional interaction between P and Cu.

REVIEW OF LITERATURE

Copper as a Micronutrient

Prior to 1927, many researchers observed that Bordeaux sprays (copper-lime mixture) often stimulated vigor and yield of crops that were not associated with the control of fungus disease (33, 37). Other workers, particularly McHargue (64), reported widespread occurrence of minute amounts of Cu in plant and animal tissues. In 1927, Bortels (13) obtained the first convincing evidence that Cu was an essential element in the nutrition of lower plants. In the same year researchers in the Florida Everglades and New York noted stimulation of the growth of many crops as a result of Cu application to muck soils (1, 30, 49). In 1931, Sommer (80) and Lipman (54) concluded from their separate studies that Cu was an essential element in the nutrition of higher plants. This was later confirmed by Arnon and Stout (3).

The essentiality of Cu in higher plant nutrition was not immediately accepted by many workers in the field. Raber (71) indicated that the requirement of plant for Cu could be due to indirect influence or antagonistic effect of other ions. Hoagland (40) suggested the desirability of confirming the specificity of the need for Cu by plants and

to show that other elements capable of existing in several states cannot replace Cu. The skepticism prompted Arnon (5) to look once again into the essentiality of Cu in plant nutrition. His results satisfied then the three criteria of essentiality, namely, (1) the element is needed for normal growth and reproduction, (2) the requirement for the element is specific and cannot be replaced by other elements, and (3) the need for the element is direct and not due to toxicity or antagonism by other elements.

Physiological Function of Cu

The roles of Cu in plant metabolism are numerous, varied and complex. Knott (50) observed that onions grown in many areas of muck soils in New York were frequently characterized by poor color and thin scales. The application of Cu sulfate to soils corrected the undesirable and abnormal condition of the onion bulbs. The blue-black discoloration of potato tubers was in part corrected by Cu application (67). Other workers (51, 62) reported that Cu was essential in the development of different plant pigments such as chlorophylls and carotenoids. Copper is also believed to be involved in protein utilization (16, 61).

Biochemical research has now established that Cu is the prosthetic group in several metallo-protein oxidizing enzymes such as polyphenol oxidase (tyrosinase), ascorbic acid oxidase and laccase (5, 21, 35, 49, 66). Arnon (4) established that polyphenol oxidase is localized in the

chloroplast, thus confirming that Cu is necessary in photosynthesis. Other workers reported the association of Cu with many enzymes involved in the electron transport system and the Kreb cycle (28).

Salisbury and Ross (76) stated that Cu is a necessary component of plastocyanin. In addition they believed that Cu may be a part of nitrate reductase and perform a catalytic role in nitrogen fixation.

Deficiency Symptoms of Cu

According to Reuther and Labanauskas (75), symptoms of Cu deficiency in higher plants vary with species and possibly with other factors. The Cu deficiency symptoms in peaches, plums, citrus and apricots include cessation of terminal growth, gum pockets under bark, defoliation, formation of multiple buds in the leaf axil, rosetting, and die-back (1, 2, 23, 26, 47).

Reed (72) and Bailey and McHargue (6) described Cu deficiency symptoms in tomatoes. The initial symptom was shown by the mature leaves consisting of the rolling up of the leaflets, appearance of chlorotic areas which later turned brown, while the young leaves curled badly and showed symptoms of water stress. In corn and sugar beets, however, initial symptoms of Cu deficiency were observed on the upper leaves and on the axil of the leaves, respectively (8, 78).

Locascio and Fiskell (55) described symptoms of Cu

deficiency in watermelons. The early symptoms consisted of upward cupping and crinkling of the young expanding leaves and necrosis of the leaf tips during expansion. Later and more severe symptoms consisted of reduced shoot growth, shortened internodes and small serrated leaves.

According to Chapman (18) Cu-deficient plants generally have less than 4 ppm Cu on dry matter basis while the range for normal growth of most plants is between 5 to 20 ppm.

Reaction of Cu with Clay

Copper and other micronutrient cations, Zn, Fe and Mn can be absorbed on the clay surface by electrostatic attraction or they can enter into specific absorption process through covalent bonding to certain functional groups on the clay surface (25). In addition, these cations can enter into crystal lattices of layer silicates by isomorphic substitution.

Copper entering the crystal lattices by isomorphic substitution is fixed Cu, in this form, it is hardly removed by extraction with neutral salts (38, 69). Cu in that state, however, may be extracted by the use of acid (15) or it can be brought into solution by lowering the soil pH (70, 73).

The availability of Cu is also adversely affected by excessive application of lime, such liming results in the formation of precipitates of cupric hydroxide and cupric

carbonates which are not readily available to plants (65, 70).

Copper in the exchange sites may exist as the divalent cupric ion, Cu^{2+}, or as the monovalent cupric ion, $CuOH^{+}$, depending upon the pH of the solution (85). In the acidic pH range, Cu is hydrolyzed and held on surfaces as $CuOH^{+}$ (14, 24). In the mildly acid system, however, hydrolysis is relatively unimportant. At pH 6, the Cu^{2+}, $CuOH^{+}$ ratio is approximately 100 : 1. It can be inferred from the observation of Krauskopf (51) that in the pH range at which most economic crops are grown, Cu in soils is probably present chiefly as the absorbed Cu^{2+} ion.

Reaction of Cu with Organic Matter

The ability of organic matter to form stable complexes with metal ions and its high capacity to fix micronutrients particularly Cu has been well established (42, 53, 79). Schnitzer and Skinner (79) stated that the stable organo-metal complex is due to the formation either of electrostatic or covalent bondings or both between the metal ions and the ligands. A later study indicated, however, that the stability of metallo-organo complex is due to the Fouss effect or coiling of the organic polymer (68).

Hodgson (42) reported that organic soils are among those most commonly deficient in Cu. This occurs since their Cu content is frequently low and their capacity to fix Cu is high. Hodgson's statement conveyed the idea that the

formation of organo-metal complexes make the metal unavailable to plants. However, in a later work by Hodgson et al. (43), it was found that organic complexing increased the total Cu concentration in solution by a factor of 100. Gupta (38) demonstrated that the addition of organic matter to soil can increase exchangeable Cu. It was also shown by Bear (7) that organo-metal complexes of humic acid contained Cu which is available to oat plants in addition to Cu that is not available.

A recent review by Stevenson and Ardakani (83) on organic matter reactions with micronutrients in soil has clarified some of the conflicting roles of organic matter regarding availability of micronutrients. According to these workers, metals in soil that occur in insoluble combinations with organic matter are largely those that are bound to components of the humic acid fraction, particularly humic acids, while the metals found in soluble complexes are mainly those associated with individual biochemical molecules such as organic acids.

Cu and P Interactions

It has been observed by many workers that the application of inorganic P to orchards and vegetable crops sometimes results in the appearance of symptoms which became known by the term exanthema and which are now recognized as Cu deficiency symptoms.

One of the earliest works relating to the Cu-P inter-

actions was conducted in Florida by Forsee and Allison (34). These workers reported that as P from superphosphate was increased, Cu contents of the leaves and fruit juice of citrus was decreased. Erwin (27) made a similar report. He found that increasing P in the soil decreased Cu in the plant, but increased Cu in the soil leachate. He added, however, that the increase of Cu in the leachate was only true up to a certain level of P beyond which Cu in the leachate was also depressed. The observation that excessive application of P induced Cu deficiency in many crops has been confirmed by many workers (9, 10, 11, 52, 74, 81, 82, 89). Locascio et al. (57) presented additional information pertaining to Cu-P interactions. These workers found that P source also contributed to this interaction. Their observation indicated that P from diammonium phosphate (DAP) depressed Cu uptake more than that from either concentrated superphosphate (CSP) or ordinary superphosphate (OSP).

There is a lack of agreement among workers about the nature of Cu-P interactions. The earlier consensus among workers was that P, when present in high amount, would fix Cu making it less available to plants (44). Forsee and Allison (34) believed that the P influence on Cu was not in the nature of straight fixation but could be an indirect effect. The idea of Cu fixation by P was disputed by Jamison (44). This worker found that Cu was more soluble in the presence of superphosphate than in soil alone. It was also shown that the presence of iron (Fe) which active-

ly tied up active phosphate group had no effect on Cu fixation (45). In another study by Jamison (46), it was observed that the amount of Cu leached from the soil was not affected by the rate of P application.

The idea of P-induced Cu fixation was also disputed by Pesch (69). In his study of ion availability as influenced by soil reactions, he found that P appeared to have no relationship to Cu fixation.

Dekock et al. (22) observed Cu-P interactions in oats. The application of high amounts of P to oats induced Cu deficiency. They suggested, however, that the aggravation of Cu deficiencies with the application of P was due to increased growth of plants and higher demand for Cu. These workers also found that N application could also enhance Cu deficiencies.

Effects of Fertilizer Placements

According to Cumings et al. (20), considerable injury to germinating bean seeds was caused by improper placement of fertilizer materials. Sayre (77) found that the greatest injury to germination occurred when fertilizer was placed in direct contact with the seeds.

Thompson (94) reported that broadcast method of fertilizer application is preferable to applying fertilizers in hills. He added that for medium to large applications (above 976 kg/ha), it is not advisable to apply fertilizers in hills or in narrow strips because of the

danger of injury to roots. A similar report was made by Watts and Watts (88). They stated that fertilizers are broadcast in crops that are planted in rows and whenever large application rates are made.

Recent findings confirmed that the effect of fertilizer placement is dependent upon rate of application, method of planting and kind of crops. Locascio et al. (58) found that at fertilizer rate of 1,680 kg/ha, watermelon yields at both band and broadcast placements were comparable. At higher fertilizer rate (3,360 kg/ha) yields increased by 40 percent when fertilizers were applied broadcast but yield increased only by 18 percent when the fertilizers were banded. In a later study by Locascio et al. (59), it was found that plant growth and yield were enhanced by broadcast applications of either N-P-K or micronutrients. Crop response particularly to micronutrients was believed due to increased efficiency of utilization with the broadcast placement and to toxicity with the band placement. Soluble salts levels, according to Fiskell et al. (31) were consistently much higher in banded than in broadcast areas.

The behavior of phosphatic materials when applied to the soil was studied by Cooke (15). He concluded that water soluble phosphates are effective if formulated into granular form instead of powder and if applied in bands. Insoluble phosphates on the other hand are most effective when formulated in powder form and applied broadcast.

MATERIALS AND METHODS

Data were obtained from two field experiments and from four greenhouse experiments. In all experiments the 'Poinsett' cultivar of cucumber was used as the test plants.

Field Experiments

Two similar experiments were conducted in 1971 and 1972 on two adjacent newly cleared areas of Leon fine sand at the Horticultural Unit in Gainesville. The soil pH was approximately 3.9 and the organic matter content was approximately 3.2 percent. Native soil P was approximately 5.5 kg/ha while soil Cu was about 1 ppm. The treatments were 80 factorial combinations of three P sources, DAP, OSP, and CSP; four P rates, 0, 28, 56, and 112 kg/ha; four Cu rates, 0, 2.24, 4.48, and 8.96 kg/ha; and two fertilizer placements, band and broadcast.

All fertilizer treatment formulations received N at the rate of 134 kg/ha, one-fourth of which was in nitrate form, and three-fourths was in the ammonium form, and 134 kg/ha of K equally from muriate of potash and sulfate of potash. The field plots were arranged in a randomized block design with three replications.

In 1971, the field was limed one week before planting and in 1972 liming was applied a month before planting. Liming, at the rate of 9,000 kg/ha $CaCO_3$, raised the pH to approximately 5.5. In both experiments, the fertilizer was applied before planting on beds 1.5 m apart. With the band placement the fertilizer was applied by hand on a single furrow located approximately 6.4 cm deep and 6.4 cm to the side of bed center. In the broadcast placement, the fertilizer was applied by hand on the entire bed surface and incorporated to a depth of approximately 18 to 20 cm.

The 'Poinsett' seeds were planted in a single row in the bed center with the use of a Planter Junior seeder. Seedlings were thinned to one every 61 cm of row. At the last thinning (30 days after seeding), the plants were side-dressed with 34 kg/ha N in the form of ammonium nitrate.

The first fruits were harvested approximately 55 days after planting. Subsequent harvests were made at 3 to 4 days intervals. A total of eight harvests were made in 1971 and five harvests in 1972. Weights of marketable fruits were taken. The yields obtained in the first three harvests were added together for early yield determinations.

Whole plant samples were collected for tissue analyses, 30 days after planting. At harvest, mature leaves were taken. Plant tissues were oven-dried and ground with a Wiley mill. Two-gram samples of the ground tissues were dry-ashed at approximately 550°C. The ash was dissolved in 1 N hydrochloric acid (HCl). The solu-

tion was then filtered and the filtrate was collected into a 50-ml volumetric flask and the volume of the filtrate was adjusted to 50 ml with 1N HCl. Afterwards a 25-ml aliquot was taken and evaporated to dryness on a hot plate.

The volume was then brought back to 10 ml with 1N HCl. This extract was taken to the Analytical Research Laboratory, Soil Science Department, University of Florida, Gainesville, where Cu and Fe were determined by an atomic absorption spectrometer. P was determined colorimetrically by phosphomolybdate method.

Greenhouse Experiments

Four greenhouse experiments were conducted in 1972 and 1973. Two of the experiments were conducted using soil and two using nutrient solutions. 'Poinsett' cucumbers were grown in all greenhouse experiments.

Soil Culture Experiments

In 1972, the treatments were factorial combinations of three Cu rates at 0, 0.03 and 2 ppm; and P rates of 0, 15, 30, 60 and 120 ppm. Treatments were replicated three times. In 1973, the treatments were the factorial combinations of three Cu rates, 0, 1 and 2 ppm and four P rates: 15, 30, 60 and 120 ppm. In both experiments, the source of Cu was copper sulfate (25.4% Cu) while P was obtained equally from di- and monosodium phosphate. Each treatment received calcium oxide at the rate of 1000 ppm. The soil

was from a virgin field of Leon fine sand. It was obtained from an area adjacent to where the first field experiment was conducted. The soil was taken from the top 18-cm depth of the profile. It was air-dried and cleaned of debris. The required fertilizer per treatment was added to 50 kg of soil which was divided equally in three crocks for the three replications. In the 1973 experiment, a similar procedure was followed except that a smaller pot was used and the fertilizer was applied in solution form. The measured solution was applied to the soil with the use of a small hand sprayer. The soil which was spread thinly on a plastic sheet was stirred while the solution was being applied.

After applying the fertilizers, the soil was placed in pots, labelled and taken to the greenhouse. In both experiments, fertilizers were applied only prior to planting.

Cucumber seeds were planted immediately after applying the treatments. Four seedlings were maintained per pot in the 1972 experiment. In 1973, there were two seedlings per pot. The plants were kept until they reached the flowering stage. At flowering, fresh and dry weights of the whole plant minus the roots were determined. In addition, the whole plant was analyzed for Cu, P, and Fe using the extraction and analytical methods described for the field experiments.

Solution Culture

The first solution culture experiment was conducted in 1972, and the second, in 1973. In the 1972 experiment, the treatments were factorial combinations of three Cu rates: 0, 0.02 and 0.2 ppm, and five P rates: 0, 15, 30, 60 and 120 ppm. The source of Cu was copper sulfate (25.4% Cu) and P was supplied equally from mono- and disodium phosphate. The experimental design was a randomized block with three replications. The nutrient solutions were prepared based on Hoagland solution No. 1 (41) with Cu and P rates being varied as listed above.

In the 1973 experiment, P rates were 30, 60 and 120 ppm and the Cu rates were the same as those used in the 1972 experiment (0, 0.02 and 0.2 ppm). In addition, N source ammonium (NH_4^+) and nitrate (NO_3^-), was introduced as a variable. A split-plot design with factorial subplots was used. Sources of N were the main plots and factorial combinations of Cu and P rates were the subplots.

Solutions were placed in gallon-size plastic containers painted black on the outside. A piece of 15 x 15 x 0.6-cm plywood drilled with four 2-cm holes around the center was used to hold seedlings on top of the container. The composition of the basic solution is presented in Table 1.

When the seedlings were 4 to 5 cm tall, they were transferred to the nutrient solutions. Cotton was wedged

Table 1. Composition of the basic solution for the 1973 greenhouse (solution culture) experiment[a]

NO_3^- solution	NH_4^+ solution
M KNO_3	0.5 M K_2SO_4
M $Ca(NO_3)_2$	0.5 M $CaCl_2$
M $MgSO_4$	M $MgSO_4$
	M $(NH_4)_2SO_4$

Milliequivalents

	K	MG	Ca	NO_3-N	NH_4-N	SO_4	CL
NO_3^- solution	5	4	10	15	0	4	0
NH_4^+ solution	5	4	10	0	15	24	10

[a]P and Cu were variables. All micronutrients except Cu were held constant. pH of the solutions was approximately 6.0.

around the stems to keep the seedlings upright. The solutions were changed once a week. At flowering stage, the fresh and dry weights of the above-ground portion of the plants were determined. Whole plant samples were ground and analyzed for Cu, P and Fe following the extraction and analytical methods described previously. In addition, analyses were made for Ca and Mg by atomic absorption method and K by the flame emission method.

Statistical Analyses

Statistical analyses of the field experiments and the 1972 greenhouse experiments were performed by the Statistical Laboratory of the Agricultural Experiment Station, Institute of Food and Agricultural Sciences (IFAS), Gainesville. The statistical analyses of the 1973 greenhouse experiments were performed by the author.

RESULTS

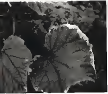
1971 Field Experiment

Variations due to soil factors were evident in the experiment. In some cases treatment effects were modified by the variability of the soil. About three weeks after planting, Cu deficiency symptoms became apparent on treatments without Cu. At the same time toxic effects of Cu were observed on the band treatments with high Cu and occurred more frequently where P was not applied or applied at low rates.

The initial symptoms of Cu deficiency were chlorosis and cupping or rolling of the leaf edges and plants appeared to be under water stress. Chlorosis progressed from the tip to the base of the leaf in the interveinal area. Complete cessation of terminal growth was often apparent at this stage. At a more advanced stage, necrosis developed on the chlorotic areas usually starting at the leaf margin (Figure 1)

Early Yields

Table 2 shows the effects of Cu and P applications on early marketable yields of cucumbers. Yields increased with increased rates of Cu applications. The increase is



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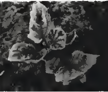

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Figure 1. Cucumber plants showing symptoms of Cu deficiency. (A) A mature leaf that shows initial symptoms of Cu deficiency. Note necrosis of the edges of the leaf. (B) A plant that exhibits more advanced symptoms of Cu deficiency. Cupping and necrosis of the edges of the leaves, interveinal chlorosis and cessation of terminal growth are prominent on a Cu-deficient plant.

Table 2. Effects of Cu and P rates on the early yields of cucumbers, 1971

P rate[z]	Cu rate[y], kg/ha				
	0	2.24	4.48	8.96	Mean
kg/ha		t/ha			
0	0.02	1.66	1.05	0.00	0.68
28	0.40	3.65	2.10	4.70	2.71
56	0.60	3.55	3.90	3.65	2.92
112	1.40	2.50	5.30	6.85	4.01
Mean	0.73	3.10	3.48	4.59	

[z]Mean P rate effects were linear at the 1% level.

[y]Mean Cu effects were linear at the 5% level.

yield with Cu rates was significantly linear (Table 3). At Cu rates of 0, 2.24, 4.48 and 8.96 kg/ha yields were 0.73, 3.10, 3.48 and 4.58 metric tons/hectare (t/ha), respectively.

The yield response to Cu was independent of P rates or sources (Table 3). It may be noted, however (Table 2), that at a Cu rate of 8.96 kg/ha, the yield was zero where P was not applied. When P application was increased to 112 kg/ha, yield was increased to 6.85 t/ha. The main effect of P rates on yield was linear (Tables 2 and 3). Yield increased with increased rate of P applications.

No interaction between Cu rates and P sources was found on yield. Similarly, the interaction between Cu rate and fertilizer placement on yield was not significant. However, main effects of P sources and fertilizer placements on early yield were significant. Among the three P sources, yield response with ordinary superphosphate was significantly higher than that with concentrated superphosphate or diammonium phosphate. Main effects of P source and placement on early yields are shown in Table 4. Significantly higher yields were obtained from treatments with broadcast fertilizer applications. Yields with the broadcast placement produced a mean of 3.94 t/ha compared to 2.01 t/ha for banded fertilizers.

Table 3. Analysis of variance of early and total cucumber yields, 1971

Sources of variation	df	Early yield	Total yield
		Mean squares	
Blocks	2	2659.42**[z]	11969.10**
Phosphorus sources			
OSP vs CSP	1	765.44**	8134.54**
OSP, CSP vs. DAP	1	314.16	765.11
Phosphorus rates			
Linear	1	1135.44**	1144.03
Quadratic	1	118.34	2392.69*[y]
Cubic	1	125.67	757.28
P rates x P sources	4	121.80	1675.02**
Cu rates			
Linear	1	2602.53**	23485.92**
Quadratic	1	368.01	2733.30*
Cubic	1	134.99	1542.12
P sources x Cu rates	6	55.89	384.26
P rates x Cu rates			
Linear x Linear	1	503.30	15.12
Remainder	8	101.44	853.73
P sources x P rates x Cu rates	12	41.90	269.99
Fertilizer placements (Fert.)	1	1486.03**	15186.10**
P sources x Fert.	2	117.02	232.42
P rates x Fert.	3	23.47	331.13
P sources x P rates x Fert.	4	96.53	451.45
Cu rates x Fert.	3	144.30	1693.92*
P sources x Cu rates x Fert.	6	152.30	681.67
P rates x Cu rates x Fert.	9	74.25	164.65
P sources x P rates x Cu rates x Fert.	12	165.36	645.82
Error	158	162.58	484.49

[y]P-values significant at the 5% (*) level.

[z]P-value significant at the 1% (**) level

Table 4. Effects of P sources and fertilizer placement on the early yields of cucumbers, 1971

Treatment	Early yield
P source[z]	t/ha
OSP	4.46
DAP	2.57
CSP	2.66
Fertilizer placement[y]	
Band	2.01
Broadcast	3.94

[z]Difference between OSP and CSP was significant at the 5% level. Yield difference between CSP and DAP was not significant.

[y]Difference between placements was significant at the 1% level.

Total Yield

The effects of Cu and P rates on total yields are shown in Table 5. Total yields increased with Cu applications. An increase in Cu application from 0 to 8.96 kg per hectare increased the total yields from 3.59 to 15.22 t/ha. The effect of Cu rate on total yield was both linear and quadratic.

Interactions between Cu rates and P rates or P sources on total yield were not significant. However, the interaction between Cu rate and fertilizer placement was significant (Table 6). With both band and broadcast placements, total yields increased with increased Cu applications. However, the increases in total yields with Cu applications were significantly greater with the broadcast placement. Mean yields at Cu rates of 0, 2.24, 4.48 and 8.96 kg/ha with the band placement were 3.12, 8.20, 6.54 and 10.60 t/ha, respectively, and with the broadcast placement total yields were at 4.10, 12.91, 16.34 and 19.83 t/ha, respectively.

The main effect of P rates on total yield was quadratic. There was a large increase in total yield as P application was increased from 0 to 28 kg/ha. A further increase in P applications resulted in a negligible increase in total yields; at P rates of 56 and 112 kg/ha, total yields were 10.95 and 10.75 t/ha, respectively.

The main effects of P sources on total yields were

Table 5. Effect of Cu and P rates on the total yields of cucumbers, 1971

P rate[z]	Cu rate[y], kg/ha				
	0	2.24	4.48	8.96	Mean
kg/ha			t/ha		
0	0.75	6.80	10.45	3.20	5.30
28	2.55	12.60	9.40	17.90	10.61
56	2.70	11.05	14.40	15.55	10.95
112	6.50	9.45	10.80	16.15	10.75
Mean	3.59	10.62	11.44	15.22	

[z]Mean P rate affects were quadratic and cubic at the 5% and 1% levels, respectively.

[y]Mean Cu rate affects were linear and quadratic at the 1% and 5% levels, respectively.

Table 6. Copper rate and placement interaction effects on total fruit yields and on tissue Cu concentrations 30 days after planting, 1971

Placement[z]	Cu rate, kg/ha 0	2.24	4.48	8.96	Mean
		Total yields t/ha			
Band	3.12	8.20	6.54	10.60	7.12
Broadcast	4.10	12.91	16.34	19.83	13.33
		*	*	*	
		Tissue Cu ppm			
Band	6.3	8.0	7.7	9.1	7.8
Broadcast	7.1	8.2	9.6	11.3	9.1
			*	*	

[z]Difference between placement significant at the 5% (*) level.

also significant. The effects of P sources and fertilizer placement on total yields are presented in Table 7. Yields obtained with OSP were significantly higher than treatment yields with either DAP or CSP. Yields obtained with DAP and CSP were comparable.

Main affects of fertilizer placements on total yields were also significant. Total yields with broadcast placement were significantly higher than total yields obtained with the band placement. A mean total yield of 7.12 t/ha was produced by treatments with the band placement and 13.33 t/ha with the broadcast placement.

An interaction between P rates and P sources on total yield was significant (Table 8). At the lower rates of P, no difference in treatment yield was found among P sources. But at the highest P rate (112 kg/ha), total yield with OSP was significantly higher than with DAP and CSP.

<u>Mineral Composition of Plant Tissues 30 Days After Planting</u>

The main effects of Cu rates, P rates, P sources and fertilizer placements are presented in Table 9, and the analyses of variance in Tables 10 and 11. The application of Cu to soil resulted in a linear increase in tissue Cu levels. With no Cu applied to the soil, foliar Cu had a mean of 6.7 ppm. At Cu rates of 2.24, 4.48 and 8.96 kg/ha, tissue Cu levels were 8.1, 8.6 and 10.2 ppm, respectively. Copper application to the soil, however, had no affect on tissue P concentrations, but did affect Fe concentration in

Table 7. Effects of P source and fertilizer placement on the total yield of cucumbers, 1971.

Treatment	Total yield
P source[z]	t/ha
OSP	14.22
DAP	9.74
CSP	8.36
Fertilizer placement[y]	
Band	7.12
Broadcast	13.33

[z]Difference between OSP and CSP was significant at the 1% level. Difference between CSP and DAP was not significant.

[y]Difference between placements was significant at the 1% level.

Table 8. Effects of P sources and P rate interactions on total yields, 1971

P sources[z]	P rate, kg/ha 28	56	112	Mean
		t/ha		
OSP	13.76	11.08	17.83	14.22
DAP	9.54	10.52	9.19	9.74
CSP	8.62	11.26	5.19	8.36
Mean	10.61	10.95	10.75	

[z]Significant difference at the 1% level existed only between OSP and DAP or CSP at P rate of 112 kg/ha.

Table 9. Main effects of P rate, Cu rate and fertilizer placement on mineral composition of plant tissues, 1971

Treatment	Time of sampling					
	30 days after planting			At harvest		
	Cu	P	Fe	Cu	P	Fe
P rates, kg/ha	ppm	%	ppm	ppm	%	ppm
0	10.9	0.48	134	3.8	0.24	81
28	8.2	0.65	126	3.7	0.36	91
56	8.1	0.78	133	3.6	0.41	81
112	8.1	0.90	126	3.4	0.53	88
F value[z]	L**Q** C**	L**Q**	C**		L**	C**
Cu rates, kg/ha						
0	6.7	0.74	133	3.2	0.47	107
2.24	8.1	0.77	123	3.7	0.40	90
4.48	8.6	0.75	134	3.5	0.39	73
8.96	10.2	0.74	126	3.9	0.37	76
F value	L**		C**	L**C*	L**Q*	L**Q** C*
Placements[y]						
Band	7.8	0.75	131	3.4	0.39	87
Broadcast	9.1	0.75	126	3.7	0.43	86
	**		**	*	*	

[z]Rate effects were linear (L), quadratic (Q), and cubic (C) at the 5% (*) and 1% (**) levels of significance.

[y]Difference between placements significant at the 5% (*) and 1% (**) levels.

Table 10. Analysis of variance of the mineral composition of plant tissues at 30 days after planting, 1971

Sources of variation	df	Cu	P^z	Fe
			Mean squares	
Blocks	2	9.6371*[y]	3.4666*	1215.03**
Phosphorus sources				
OSP vs. CSP	1	34.7117**[x]	0.0756	303.34
SOP, CSP vs. DAP	1	25.6669**	0.1672	744.19*
Phosphorus rates				
Linear	1	52.2161**	395.4347**	412.57
Quadratic	1	84.2906**	24.0464**	122.14
Cubic	1	32.5494**	0.0851	2698.59**
P rates x P sources	4	6.5226*	3.5069**	1326.65**
Cu rates				
Linear	1	364.5838**	0.0917	448.97
Quadratic	1	5.6358	1.0779	6.71
Cubic	1	6.0002	1.7412	5076.13
P sources x Cu rates	6	5.8165*	2.2035*	1320.67**
P rates x Cu rates				
Linear x Linear	1	16.8947*	6.3424**	2745.26**
Remainder	8	10.5276**	2.9123**	2673.49**
P sources x P rates x Cu rates	12	6.7509**	2.8395**	2477.31**
Fertilizer placements (Fert.)	1	102.1815**	0.0082	1306.67**
P sources x Fert.	2	4.7467	9.3356**	722.76*
P rates x Fert.	3	16.5389**	0.9042	315.48
P sources x P rates x Fert.	4	2.4858	0.6782	980.15**
Cu rates x Fert.	3	13.5539**	0.1401	862.72**
P sources x Cu rates x Fert.	6	4.7506	2.8151**	2045.45**
P rates x Cu rates x Fert.	9	14.7868**	1.7536*	641.55**
P sources x P rates x Cu rates x Fert.	12	6.1828**	0.7199	1652.38**
Error	158	2.7441	0.9131	187.67

[z] Mean squares for P must be multiplied by 10^{-2}

[y] Significant at the 5% level.

[x] Significant at the 1% level.

Table 11. Analysis of variance of the mineral composition of the plant tissues at harvest stage, 1971

Sources of variation	df	Mineral composition Cu	P	Fe
		Mean squares		
Blocks	2	16.9290**[z]	0.48952**	310.08
Phosphorus sources				
OSP vs. CSP	1	1.2100	0.11903**	2047.56**
OSP, CSP vs. DAP	1	3.3075	0.04441	733.72
Phosphorus rates				
Linear	1	4.2778	1.84435**	38.18
Quadratic	1	0.1892	0.02456	135.05
Cubic	1	0.0027	0.03384	4280.70**
P rates x P sources	4	1.7222	0.01910	107.51
Cu rates				
Linear	1	13.3681**	0.17100**	28424.32**
Quadratic	1	0.6268	0.0674*	13838.84**
Cubic	1	5.6379*[y]	0.00841	823.97*
P sources x Cu rates	6	1.7596	0.03551	2796.77**
P rates x Cu rates				
Linear x Linear	1	0.0011	0.00475	82.89
Remainder	8	1.6619	0.01644	1423.84**
P sources x P rates x Cu rates	12	1.2300	0.02904	583.44*
Fertilizer placements (Fert.)	1	6.9700*	0.10753*	153.60
P sources x Fert.	2	1.4350	0.02307	1771.79**
P rates x Fert.	3	1.9904	0.03652	327.67
P sources x P rates x Fert.	4	3.3302	0.00888	268.99
Cu rates x Fert.	3	1.2878	0.00329	231.93
P sources x Cu rates x Fert.	6	2.4517	0.01178	1748.73**
P rates x Cu rates x Fert.	9	1.3587	0.02060	626.10**
P sources x P rates x Cu rates x Fert.	12	1.1715	0.01648	754.26**
Error	158	1.2689	0.01747	192.05

[z]Significant at the 1% level.

[y]Significant at the 5% level.

the plant tissues. The effects of soil Cu application on Fe levels in the tissues followed a cubic pattern. Cu rates from 0 to 2.24 kg/ha decreased Fe levels from 133 to 123 ppm. Increasing soil Cu application rate to 4.48 kg/ha brought up tissue Fe level to 134 ppm. But a further increase in soil application resulted in decreased Fe levels in the tissues. Soil application of P decreased both the Fe and Cu concentrations in the plant tissues, but resulted in increased concentration of tissue P.

Tissue P concentrations were not affected by fertilizer placement; P concentrations at both placements were similar. Tissue Cu levels were significantly higher with the broadcast placement.

Mineral Composition of Leaf Tissues at Harvest

The treatments induced significant variations in the tissue levels of Cu, P and Fe at harvest (Tables 9 and 11). The application of Cu to the soil resulted in increased tissue Cu concentrations but decreased the tissue concentrations of P and Fe. The application of P to the soil on the other hand increased tissue P but decreased tissue Cu and Fe levels.

Concentrations of Cu in the leaf tissues were significantly higher with broadcast placement than with band placement. However, the concentrations of P in the leaf tissues were higher with the band placement than with the broadcast placement.

Relationships between Yields and Mineral Composition of Plant Tissues

The correlation coefficients between yields and mineral concentrations in the plant tissues at two sampling dates are presented in Table 12.

Positive correlations were found between early yields and tissue Cu levels at both sampling dates. The correlation between early yield and tissue P concentrations at 30 days after planting was also significantly positive. However, at harvest, the correlation between tissue P levels and early yield was negative. The Fe tissue levels at both sampling dates did not correlate with early yields.

Early yields were positively correlated with total yields. Positive correlations between total yields and tissue Cu levels at both sampling dates were also significant. No correlation, however, was found between total yields and tissue P concentrations at 30 days after planting. At harvest, tissue P levels were negatively correlated with total yields. Again, there was no correlation between total yields and tissue Fe concentrations at both sampling periods.

Correlations of Levels of Mineral Elements in the Plant Tissues

At 30 days after planting, correlation between tissue Cu levels and tissue P levels was positive. However,

Table 12. Correlation between early and total yields and mineral composition of plant tissues at two sampling dates, 1971

Factor	Total yield	Early yield
	Correlation coefficients, r	
Early yield	0.7733*[z]	
30 days after planting		
Cu	0.2303*	0.1506*
P	0.0893	0.1582*
Fe	-0.0040	0.0373
At harvest		
Cu	0.1957*	0.2399*
P	-0.3384*	-0.2762*
Fe	-0.0042	-0.0126

[z]Significant at the 5% level.

at harvest the correlation of the Cu and P levels in the tissues was negative. Correlation between P and Fe levels in tissues 30 days after planting was negative. At harvest, the correlation between the levels of P and Fe in the tissues was positive (Table 13).

1972 Field Experiment

The experimental area for this experiment was more uniform than that for the preceding year. This was indicated by the fairly uniform crop growth in all blocks. Symptoms of Cu deficiency developed at a later period compared to that of the previous year's experiment. Deficiency symptoms were observed about a month after planting on treatments that received high P rates and where no or low Cu was applied.

Early Yields

The soil application of Cu resulted in increased early yields. The increase in yield in relation to Cu application was significantly linear, quadratic and cubic indicating that at some point the application rate of Cu had exceeded crop requirement. The effects of Cu and P rates on early yield are shown in Table 14. The application of 2.24 kg Cu/ha resulted in an increase in early yield of about 100 percent. Further increases in Cu produced only a slight increase in early yield. With no Cu, mean yield was 7.03 t/ha. The application of 2.24 kg

Table 13. Relationship between the levels of mineral elements in plant tissues at two sampling dates, 1971

	Mineral Composition					
	30 days after planting			At harvest		
Elements	Cu	P	Fe	Cu	P	Fe
	Correlation coefficient, r					
30 days after planting						
Cu		0.1969*[a]	0.1247	0.1847*	-0.0889	[illegible]
P			-0.1747*	0.0755	0.3583*	-0.0440
Fe				0.0104	-0.0522	-0.0487
At harvest						
Cu					-0.1940*	-0.0487
P						0.1939*

[a]Significant at the 5% level

Table 14. Effects of Cu and P rates on the total yields of cucumbers, 197[illegible].

P rate^z	Cu rate^y, kg/ha 0	2.24	4.46	8.96	Mean
Kg/ha		t/ha			
0	5.55	9.48	13.44	8.44	9.23
28	6.45	16.93	16.20	14.60	13.54
56	8.39	15.84	15.95	17.14	14.34
112	6.75	12.12	12.41	17.00	12.07
Mean	7.03	14.41	14.73	15.47	

^{z}Mean P rate effects were quadratic at the 1% level.

^{y}Mean Cu rate effects were linear, quadratic and cubic at the 1% level of significance.

Cu/ha increased yields to 14.41 t/ha. Cu applications of 4.48 and 8.96 kg/ha produced mean yields of 14.73 and 15.47 t/ha, respectively.

An interaction between P rates and Cu rates on early yield was significant. A reduction in yield occurred when either P or Cu was limiting. Highest yield was obtained with application of 56 kg P/ha and 8.96 kg Cu/ha.

Fertilizer placements also interacted with Cu effects (Table 15). Without Cu, yields with both placements were the same, but at higher Cu rates, yields between fertilizer placements were significantly different. With the broadcast placement, an increase in Cu application from 0 to 8.96 kg/ha increased early yields by approximately 26% percent. But with the band placement, Cu application beyond 2.24 kg/ha only brought a slight increase in yield. At the highest rate of Cu (8.96 kg/ha), yield was even slightly decreased.

Main effects of P sources on early yield were not significant. Similar yield was produced with all three P sources (Table 16).

Main effects of fertilizer placement on early yields were significant. Treatment yields with the broadcast placement were significantly higher than the yields of those treatments which received banded fertilizer.

Total Yields

The effects of Cu rate on total yields were linear, quadratic, and cubic (Table 17). The main effects of Cu

Table 15. Effects of Cu rate x placements interactions on early and total yields and tissue Cu concentrations 30 days after planting, 1972

		Cu rate, kg/ha				
Response	Placement[z]	0	2.24	4.48	8.96	Mean
Total yield (t/ha)	Band	18.03	27.18	28.15	27.86	25.31
	Broadcast	19.70	37.06	37.52	40.59	33.72
			*	*	*	
Early yield (t/ha)	Band	6.01	9.82	9.87	9.51	[illegible]
	Broadcast	8.04	19.01	19.57	21.47	[illegible]
			*	*	*	
Tissue Cu (ppm)	Band	5.6	5.1	5.6	6.1	[illegible]
	Broadcast	4.3	5.7	7.1	8.8	[illegible]
		*		*	*	

[z]Difference between placements was significant at the 5% level.

Table 16. Main effects of P sources and fertilizer placements on the early yields of cucumbers, 1972

Treatment	Early yield
P source[z]	t/ha
OSP	12.86
DAP	12.57
CSP	14.53
Fertilizer placement[y]	
Band	8.81
Broadcast	17.01

[z]P source effects were not significant.

[y]Difference between placements significant at the 1% level.

Table 17. Analysis of variance of early and total cucumber yields, 1972

Source of variation	df	Early yield	Total yield
		Mean squares	
Blocks	2	914.01**[z]	95.68
Phosphorus sources			
OSP vs. CSP	1	419.23	567.23
OSP, CSP vs. DAP	1	255.61	672.00
Phosphorus rates			
Linear	1	1.02	488.98
Quadratic	1	2210.96**	1333.21
Cubic	1	105.75	1548.26*[y]
P rates x P sources	4	95.39	198.29
Cu rates			
Linear	1	6799.32**	22748.38**
Quadratic	1	3914.18**	12664.55**
Cubic	1	1044.91**	3237.64**
P sources x Cu rates	6	129.15	243.42
P rates x Cu rates			
Linear x Linear	1	504.17*	1419.11*
Remainder	8	239.86*	366.12
P sources x P rates x Cu rates	12	72.20	494.49
Fertilizer placements (Fert.)	1	16968.02**	17829.61**
P sources x Fert.	2	44.52	139.11
P rates x Fert.	3	219.89	646.98
P sources x P rates x Fert.	4	22.31	109.93
Cu rates x Fert.	3	1156.21**	1408.03**
P sources x Cu rates x Fert.	6	99.57	178.64
P rates x Cu rates x Fert.	9	48.00	128.69
P sources x P rates x Cu rates x Fert.	12	73.07	292.55
Error	158	115.67	360.13

[z]Significant at the 1% level.
[y]Significant at the 5% level.

rates are shown in Table 18. A very large increase in yield was obtained with the application of 2.24 kg Cu/ha, beyond this rate of application however, only slight increases in yield were obtained.

Phosphorus and Cu rates interacted in their effects on total yields (Table 18). The nature of the interaction was the same as that observed with early yields. Application of high rates of Cu with low P levels resulted in a yield reduction. High P rates with low Cu levels also resulted in decreased yields. Yields were highest, however, when both elements were present in adequate amounts.

Interaction between fertilizer placements and Cu rates was also significant (Table 17). The nature of the interaction, presented in Table 15, was the same as that described for early yields. Without Cu, yields between placements were the same. But yields between placements differed significantly with an increase in Cu application. With the band placement, yield was highest at 4.48 kg Cu/ha and slightly decreased beyond this application rate. With the broadcast placement, highest yield was obtained at Cu application rate of 8.96 kg/ha.

No significant effect on total yields was attributable to P sources. Comparable yields were produced by treatments grown with the different sources of P. Main effects of P sources are shown in Table 15.

Main effects of fertilizer placement on total yields were significant (Tables 17 and 19). Yields were higher

Table 18. [illegible] and P rates [illegible] yields of cucumbers, 19[illegible].

P rate[z]	Cu rate[y], kg/ha				
	0	2.24	4.48	8.96	Mean
kg/ha	t/ha				
0	19.75	24.41	31.51	29.61	26.32
28	19.95	37.10	36.71	33.66	31.86
56	19.54	33.54	31.71	34.08	29.72
112	16.81	29.29	30.52	36.47	28.02
Mean	18.87	32.12	31.37	34.23	

[z]Mean P rate effects were cubic at the 1% level of significance.

[y]Mean Cu rate effects were linear, quadratic, and cubic at the 1% level of significance.

Table 19. Main effects of P source and fertilizer placement on the total yields of cucumbers, 1972.

Treatment	Total yield
P source[z]	t/ha
OSP	29.51
DAP	28.65
CSP	31.45
Fertilizer placement[y]	
Band	25.31
Broadcast	33.72

[z]P source effects were not significant.

[y]Difference between placements was significant at the 1% level.

with the broadcast placement ([illegible] t/ha) than with the band placement (25 31 t/ha).

Mineral Composition of Plant Tissues 30 Days after Planting

Application of Cu to the soil resulted in increased levels of Cu in the tissues but did not affect tissue P and Fe concentrations. On the other hand, P applications decreased Cu and Fe contents but increased tissue P levels significantly. The main effects of P sources, P rates and Cu rates on tissue composition at 30 days after planting and at harvest are shown in Table 20.

Tissue Cu levels at 30 days after planting were influenced by an interaction between P and Cu rates. The interaction is shown in Table 21. Tissue Cu levels increased with increased Cu rate applications but the increase was much greater where P was not applied.

Both P sources and fertilizer placements had no effect on tissue P levels but significantly affected tissue Cu levels; Cu levels with DSP were higher than with the other two sources.

An interaction between Cu rate and fertilizer placement on tissue Cu levels was also found (Table 22). Cu tissue levels at the 0 and the 2 24 kg Cu/ha application were the same for both placements, but, at the higher Cu application rates differences in tissue Cu levels between placements were observed (Table 23). Tissue Cu levels increased with both placements with an increase in the rate

Table 20. Main effects of P [illegible] rates and fertilizer placements on mineral composition of plant tissues, 1972

	Time of sampling					
	30 days after planting			At harvest		
Treatment	Cu	P	Fe	Cu	P	Fe
P rates, kg/ha	ppm	%	ppm	ppm	%	ppm
0	6.9	0.42	158	3.2	0.24	99
28	6.2	0.67	146	3.0	0.37	95
56	5.7	0.79	135	2.7	0.47	90
112	5.9	0.90	136	2.4	0.59	92
P value[z]	L*Q**	L**Q**	L**Q**	L**	L**Q**	L**Q**
Cu rates, kg/ha						
0	4.9	0.74	142	2.2	0.48	104
2.24	5.4	0.74	140	2.7	0.45	90
4.48	6.3	0.76	137	2.8	0.45	90
8.96	7.4	0.75	142	3.2	0.43	8.8
F value	L**			L**	L**	L**Q** C**
Fertilizer Placements[y]						
Band	5.6	0.76	147	2.5	0.47	95
Broadcast	6.5	0.73	135	2.9	0.43	91
	*		**	**	**	**

[z]Rate effects were linear (L), quadratic (Q), and cubic (C) at the 5% (*) and 1% (**) levels of significance.

[y]Difference between placements significant at the 5% (*) and 1% (**) levels.

Table 21. Effects of the interaction of Cu and P rates on the tissue Cu concentrations 30 days after planting, 1972[z]

P rate	Cu rate, kg/ha				
	0	2.24	4.48	8.96	Mean
kg/ha			ppm		
0	4.9	5.5	6.6	10.5	6.9
28	4.7	6.0	6.1	8.0	6.2
56	4.4	5.2	6.4	6.6	5.7
112	5.7	4.9	6.2	6.8	5.9
Mean	4.9	5.4	6.3	7.4	

[z]Linear x linear interactions between P and Cu rates were significant at the 1% level.

Table 22. Analysis of variance of the mineral composition of plant tissues 30 days after planting, 1972

Source of variation	df	Cu	P	Fe
		Mean squares		
Blocks	2	2.9425	0.02543	912.93
Phosphorus sources				
OSP vs. CSP	1	20.8544**[z]	0.00640	261.35
OSP, CSP vs. DAP	1	0.0112	0.08898	189.34
Phosphorus rates				
Linear	1	11.5081*[y]	4.05696**	7273.61**
Quadratic	1	18.3717	0.64798**	5212.86**
Cubic	1	0.6071	0.03214	353.13
P rates x P sources	4	7.6023*	0.03549	2846.95**
Cu rates				
Linear	1	218.8648**	0.00284	0.11
Quadratic	1	0.0212	0.01221	431.60
Cubic	1	2.1601	0.00439	23.64
P sources x Cu rates	6	3.4863	0.02251	1236.62**
P rates x Cu rates				
Linear x Linear	1	38.7645**	0.00586	11753.31**
Remainder	8	5.6621*	0.01354	2073.64**
P sources x P rates x Cu rates	12	8.7932**	0.03990	2644.60**
Fertilizer placements (Fert.)	1	45.3270**	0.04214	9626.67
P sources x Fert.	2	0.5967	0.18301*	74.06
P rates x Fert.	3	1.6888	0.00194	1625.95**
P sources x P rates x Fert.	4	0.7290	0.02382	622.36
Cu rates x Fert.	3	43.0419**	0.02270	539.81
P sources x Cu rates x Fert.	6	1.5409	0.01627	645.85
P rates x Cu rates x Fert.	9	2.5135	0.03544	1400.52**
P sources x P rates x Cu rates x Fert.	12	3.0725	0.01731	1293.59**
Error	158	2.3702	0.04616	353.95

[z]Significant at the 1% level.
[y]Significant at the 5% level.

Table 23. Copper rate and placement interaction on total yield and tissue Cu concentration at harvest, 1972.

	Cu rate, kg/ha				
Placement[z]	0	2.24	2.48	8.96	Mean
		Total yield t/ha			
Band	18.03	27.18	28.15	27.86	25.30
Broadcast	19.70	37.06	37.52	40.59	33.72
		*	*	*	
		Tissue Cu ppm			
Band	2.2	2.6	2.6	2.7	2.5
Broadcast	2.2	2.7	3.1	3.7*	2.7

[z]Difference between placement significant at the 5% (*) level.

of Cu application but the increase was greater with the broadcast placement

Mineral Composition at Harvest

The analysis of variance of Cu, P and Fe levels at harvest are shown in Table 24. Again, it can be seen that the treatments exerted significant influence on the mineral composition of tissues.

Application of Cu resulted in a significant increase in the tissue Cu levels but significantly decreased tissue P levels. The soil application of P on the other hand, increased tissue P levels but decreased tissue Cu levels significantly (Table 20).

Higher tissue P and Cu levels were obtained where OSP was applied. Placement also affected tissue P and Cu concentrations. Tissue P was higher with band placement and Cu concentrations was higher with the broadcast placement. Fertilizer placements and Cu rates also interacted in their effects on tissue Cu levels. Tissue Cu levels were the same at both placements at the low Cu rate but differed significantly between placements as Cu application rate was increased. At higher Cu rates, tissue Cu levels were higher with the broadcast placement.

Relationship between Yields and Mineral Composition of Plant Tissues

The correlation coefficients between yields and tissue mineral composition 30 days after planting and at harvest

Table 24. Analysis of variance of early and total cucumber yields, 1972

Source of variation	df	At harvest		
		Cu	P[z]	Fe
		Mean squares		
Blocks	2	33.7666**[y]	0.7213	202.963**
Phosphorus sources				
OSP vs. CSP	1	21.1600**	4.1006**	154.174
OSP, CSP vs DAP	1	0.7008	0.6000	119.280
Phosphorus rates				
Linear	1	17.9844**	272.5365**	777.857**
Quadratic	1	0.2698	10.5299**	1036.702**
Cubic	1	0.3726	0.0019	138.553
P rates x P sources	4	0.6747	0.7934	436.234**
Cu rates				
Linear	1	29.2640**	6.2321**	5763.543
Quadratic	1	1.6667	0.2972	2802.805**
Cubic	1	0.6740	1.1521	1280.401**
P sources x Cu rates	6	3.3906	0.7235	400.313**
P rates x Cu rates				
Linear x Linear	1	3.2138	0.9792	138.193
Remainder	8	1.3151	0.8579	202.830**
P sources x P rates x Cu rates	12	1.5150	1.544**	216.163**
Fertilizer placements (Fert.)	1	8.9707**	12.6042	1033.350**
P sources x Fert.	2	2.0126	1.2684	47.727
P rates x Fert.	3	3.2606*[x]	0.9423	401.652**
P sources x P rates x Fert.	4	1.8822	0.1874	219.416**
Cu rates x Fert.	3	3.3606*	1.5771	919.583*
P sources x Cu rates x Fert.	6	2.0341	0.7239	197.918**
P rates x Cu rates x Fert.	9	1.1100	0.4704	451.216**
P sources x P rates x Cu rates x Fert.	12	1.4967	0.3659	235.518**
Error	158	1.2318	0.6153	43.034

[z]Mean squares were multiplied by 10^{-2}.
[y]Significant at the 1% level.
[x]Significant at the 5% level.

are presented in Table 25. A positive correlation was found between total yield and early yield. At both sampling periods, Cu levels were also positively correlated with total yields. No correlations between total yield and tissue P level 30 days after planting existed, but tissue P level at harvest was negatively correlated with total yield. Similarly, Fe levels at both sampling dates were negatively correlated with total yields.

Early yields were positively correlated with Cu levels at both sampling dates. But Fe levels at both sampling dates and tissue P levels at harvest were all negatively correlated with early yields.

Thirty days after planting no correlation was found between Cu levels and P levels in the plant tissues (Table 26). But Fe was positively correlated with Cu and negatively with P levels. Significant correlations also existed in the levels of elements between sampling dates.

Pooled Analysis of Data from 1971 and 1972 Field Experiments

In order to evaluate the overall effects of treatments over the two-year period, experimental data from 1971 and 1972 were pooled and treated statistically.

Total Yields

Since total and early yields were highly and positively correlated, emphasis in the pooled analysis was given only to total yields.

Table 25. Correlation between early and total yields and mineral composition of plant tissues at two sampling dates, 1972

Factor	Total yield	Early yield
	Correlation coefficient, r	
Early yield	0.8272*[z]	
30 days after planting		
Cu	0.2718*	0.2495*
P	-0.0574	0.0061
Fe	-0.1726*	-0.2559*
At harvest		
Cu	0.2220*	0.2678*
P	-0.2860*	-0.2302*
Fe	-0.3812*	-0.3795*

[z]Significant at the 5% level.

Table 26. Relationship between the levels of mineral elements in plant tissues at two sampling dates, 1972

Elements	Foliar Mineral Composition: 30 days after planting Cu	P	Fe	At harvest Cu	P	Fe
	Correlation coefficient, r					
30 days after planting						
Cu		0.0848	0.2110*[z]	0.2683*	-0.2042*	[illegible]
P			-0.1417*	-0.2205*	0.4900*	0.1600*
				0.1239	-0.1852	0.1769*
At harvest						
Cu					-0.2775*	0.0028
P						0.0202

[z]Significant at the 5% level.

The analysis of variance of yields and mineral composition of plant tissues is presented in Tables 27, 28, and 29. Significance variations in yields, except for the interaction between Cu and fertilizer placement, were all due to main effects of P sources, P rates, Cu rates and fertilizer placements.

The effects of Cu application on total yield were linear, quadratic and cubic. Yield increased with increases in Cu application rates. It can be seen, however, that considerable increase in yield was only obtained with an increase in Cu applications from 0 to 2.24 kg/ha (Table 30), Cu application beyond 2.24 kg/ha rate resulted in a slight increase in total yield.

The effect of Cu rates on total yield was independent of P rates or P sources but not of fertilizer placements. An interaction between Cu rates and fertilizer placements was significant. Without Cu, yields were similar for both placements. An increase in Cu application increased yields with both placements. Maximum yield was obtained at the Cu application rate of 8.96 kg/ha with both placements. However, yield increased 153.5 percent with broadcast placement and only 81.8 percent with band placement. Table 31 shows the interaction.

Main effects of P rates on yield were also significant. Rate effects were both quadratic and cubic. The application of 28 kg/ha increased total yields from 15.81 to 21.23 t/ha. But further increases in P applications

Table 27. Pooled analysis of variance of early and total yields, 1971 and 1972 field experiments

Sources of variation	df	Early yield	Total yield
		Mean squares	
Years (Y)	1	42469.22**[z]	140812.03**
Blocks/Y	4	1741.72**	6032.39**
Phosphorus sources			
OSP vs. CSP	1	25.86	2202.82*
OSP, CSP vs. DAP	1	568.26*[y]	1427.84
Phosphorus rates			
Linear	1	602.34*	68.57
Quadratic	1	1676.16**	3643.00**
Cubic	1	230.99	2235.58*
P sources x P rates	4	69.11	1214.56*
Y x P sources	2	580.16*	3250.11*
Y x P rates	3	395.90*	573.77
Y x P sources x P rates	4	148.08	658.76
Cu rates			
Linear	1	8907.52**	46231.35**
Quadratic	1	3385.55**	13582.46**
Cubic	1	956.52**	4624.35**
Y x Cu rates	3	542.12**	657.92
P sources x Cu rates	6	75.07	111.48
P rates x Cu rates			
Linear x Linear	1	1007.47**	863.59
Remainder	8	163.64	643.14
P sources x P rates x Cu rates	12	94.33	496.98
Y x P sources x Cu rates	6	109.97	397.95
Y x P rates x Cu rates	9	107.76	584.04
Y x P sources x P rates x Cu rates	12	19.77	267.50
Fertilizer placements (F)	1	14248.48**	32962.70

Table 27 (Continued)

Sources of variation	df	Early yield	Total yield
		Mean squares	
Y x P	1	4205.57**	53.00
P sources x F	2	36.36	44.00
P rates x F	3	178.72	774.53
P sources x P rates x F	4	77.01	256.55
Y x P sources x F	2	125.18	327.53
Y x P rates x F	3	64.63	203.58
Y x P sources x P rates x F	4	55.15	304.83
Cu rates x F	3	1039.37**	2859.39**
Y x Cu rates x F	3	261.14	242.56
P sources x Cu rates x F	6	185.52	599.37
P rates x Cu rates x F	9	37.20	41.73
P sources x P rates x Cu rates x F	12	58.66	478.85
Y x P sources x Cu rates x F	6	66.35	260.84
Y x P rates x Cu rates x F	9	85.04	251.62
Y x P sources x P rates x Cu rates x F	12	179.77	459.42
Error	316	139.12	422.31

[z]Significant at the 1% level.
[y]Significant at the 5% level.

Table 28. Pooled analysis of variances of the mineral composition of plant tissues 30 days after planting, 1971 and 1972 field experiments

Sources of variation	df	Cu	P	Fe
			Mean squares	
Years (Y)	1	692.4005**[z]	0.00001	17860.80*
Blocks/Y	4	6.2898*[y]	0.03005	1063.98**
Phosphorus sources				
OSP vs. CSP	1	0.8778	0.00138	563.92
OSP, CSP vs. DAP	1	12.3028*	0.05753	91.39
Phosphorus rates				
Linear	1	56.3755**	8.01098**	5575.40**
Quadratic	1	90.6829**	0.86505**	1911.96**
Cubic	1	12.1329*	0.01127	549.67
P sources x P rates	4	12.2562**	0.04548	1243.64**
Y x P sources	2	34.0318**	0.01946	421.46
Y x P rates	3	13.4506**	0.02182	2711.95**
Y x P sources x P rates	4	1.8687	0.02508	2929.96**
Cu rates				
Linear	1	574.2033*	0.00030	231.48
Quadratic	1	3.1743	0.02296	165.34
Cubic	1	0.4800	0.00216	2193.28**
Y x Cu rates	3	6.4693	0.00767	1127.36**
P sources x Cu rates	6	3.4860	0.03822	2213.34**
P rates x Cu rates				
Linear x Linear	1	53.4209**	0.05391	12929.60**
Remainder	8	12.8337**	0.02852	2152.26**
P sources x P rates x Cu rates	12	8.0873	0.05036	4017.49
Y x P sources x Cu rates	6	5.8168*	0.00633	344.00
Y x P rates x Cu rates	9	3.2318	0.01428	2480.88**

Table 28 (Continued)

Sources of variation	df	Cu	P	Zn
			Mean squares	
Y x P sources x P rates x Cu rates	12	7.4568**	0.01802	1104.42**
Fertiliser placements (F)	1	141.8100**	0.02296	9013.33**
Y x F	1	5.6985	0.01925	1920.00**
P sources x F	2	0.9922	0.24548**	607.92
P rates x F	3	6.3630	0.00559	574.74
P sources x P rates x F	4	1.5224	0.00622	1470.28**
Y x P sources x F	2	4.3512	0.03090	188.90
Y x P rates x F	3	11.8647**	0.00540	1366.69**
Y x P sources x P rates x F	4	1.5924	0.02438	132.23
Cu rates x F	3	45.9587**	0.00834	1301.80**
Y x Cu rates x F	3	10.5372**	0.01576	100.73
P sources x Cu rates x F	6	3.7149	0.01938	1014.81**
P rates x Cu rates x F	9	7.6380**	0.04518	955.17**
P sources x P rates x Cu rates x F	12	2.6805	0.01806	2139.16**
Y x P sources x Cu rates x F	6	2.5764	0.02504	1676.50**
Y x P rates x Cu rates x F	9	9.6022*	0.01060	1086.92**
Y x P sources x P rates x Cu rates x F	12	6.5747**	0.00645	706.81**
Error	316	2.5572	0.02765	270.81

[z]Significant at the 1% level.

[y]Significant at the 5% level.

Table 29. Pooled analysis of variance of the mineral composition of [illegible] harvest. 1971 and 1972 field experiments

Sources of variation	df	Cu	P	Fe
			Mean squares	
Year (Y)	1	87.8085	0.18174	4979.41*
Blocks/Y	4	25.3478**	0.24837**	256.52
Phosphorus sources				
OSP vs. CSP	1	16.2450**	0.01015	1662.72**
OSP, CSP vs. DAP	1	3.5267	0.00828	722.34*
Phosphorus rates				
Linear	1	19.9022**	4.52685**	235.69
Quadratic	1	0.4554	0.11579**	960.05**
Cubic	1	0.1559	0.01613	2979.76**
P sources x P rates	4	2.0814	0.01347	383.01*
Y x P sources	2	3.3033	0.09570**	334.84
Y x P rates	3	0.8610	0.02489	743.85**
Y x P sources x P rates	4	0.3156	0.01357	160.74
Cu rates				
Linear	1	41.0949**	0.21989**	29893.34**
Quadratic	1	2.1688	0.06091*	14548.79**
Cubic	1	5.1055*	0.01981	25.05
Y x Cu rates	3	0.9561	0.01412	2322.24**
P sources x Cu rates	6	3.6490**	0.01339	1790.25**
P rates x Cu rates				
Linear x Linear	1	1.6673	0.00045	3.51
Remainder	8	0.8489	0.01447	643.11**
P sources x P rates x Cu rates	12	1.4673	0.01833	329.16
Y x P sources x Cu rates	6	1.5012	0.02956*	1406.83**
Y x P rates x Cu rates	9	2.0636	0.01094	898.46**
Y x P sources x P rates x Cu rates	12	1.2777	0.02616*	470.44**

Table 29 (Continued)

Sources of variation	df	Cu	P	Fe
			Mean squares	
Fertilizer placements (F)	1	15.8777**[z]	0.00037	991.83**
Y x F	1	0.0630	0.23320**	195.08
P sources x F	2	2.2296	0.03348	962.39**
P rates x F	3	2.6422	0.02324	362.53*
P sources x P rates x F	4	3.7158*[y]	0.00904	113.56
Y x P sources x F	2	0.7182	0.00228	857.19**
Y x P rates x F	3	2.1755	0.02270	366.79*
Y x P sources x P rates x F	4	1.4966	0.00171	374.84*
Cu rates x F	3	2.3617	0.00598	930.29**
Y x Cu rates x F	3	1.6866	0.01309	221.[illegible]
P sources x Cu rates x F	6	1.4664	0.01145	[illegible]
P rates x Cu rates x F	9	0.7721	0.01616	713.[illegible]
P sources x P rates x Cu rates x F	12	1.1985	0.00938	373.[illegible]
Y x P sources x Cu rates x F	6	3.0193*	0.00757	989.16**
Y x P rates x Cu rates x F	9	1.6966	0.00516	364.29**
Y x P sources x P rates x Cu rates x F	12	1.4697	0.01301	623.86**
Error	316	1.2503	0.01181	127.54

[z]Significant at the 1% level.

[y]Significant at the 5% level.

Table 30. Main effects of P sources, P rates, Cu rates and fertilizer placements on yield and mineral composition of plant tissues, pooled analysis

Treatment	Total yield	30 days after planting: Cu	30 days after planting: P	30 days after planting: Fe	At harvest: Cu	At harvest: P	At harvest: Fe
P sources	t/ha	ppm	%	ppm	ppm	%	ppm
OSP	21.86	6.9	0.79	135	3.3	0.44	91
DAP	19.20	7.3	0.76	133	3.2	0.46	91
CSP	19.90	7.0	0.79	132	2.8	0.45	86
P rates, kg/ha							
0	15.81	8.9	0.45	146	3.5	0.24	90
28	21.23	7.2	0.66	136	3.3	0.36	93
56	20.34	6.9	0.78	134	3.1	0.44	86
112	19.88	7.0	0.90	131	2.9	0.56	90
F value[z]	L**Q**	L**Q**C*	L**Q**	L**Q**	L**	L**Q**	Q**C**
Cu rate, kg/ha							
0	11.23	5.8	0.74	138	2.7	0.47	105
2.24	21.37	6.8	0.75	132	3.2	0.42	90
4.48	21.40	7.5	0.75	136	3.2	0.42	81
8.96	24.72	8.8	0.74	134	3.6	0.41	82
F value	L**Q**C**	L**		C**	L**	L**Q*	L**Q**
Placement[y]							
Band	16.22	6.7	0.75	139	3.0	0.43	91
Broadcast	23.52	7.8	0.74	131	3.3	0.43	88
		**		**	**		**

[z]Rate effects were linear (L) and quadratic (Q) and cubic (C) at the 5% (*) and 1% (**) levels of significance.
[y]Difference between placement significant at the 1% (**) level as indicated.

Table 31. Effects of Cu rates x placement interactions on total yields and tissue Cu concentrations at harvest

	Cu rate, kg/ha				
Placement[z]	0	2.24	4.48	8.96	Mean
			Total yield t/ha		
Band	10.58	17.69	17.34	19.23	16.22
Broadcast	11.90	24.98	26.91	30.21	23.52
		*	*	*	
			Tissue Cu ppm		
Band	2.6	3.0	3.0	3.2	3.0
Broadcast	2.6	3.4	3.3	4.0 *	3.3

[z]Difference between placements significant at the 5% (*) level

resulted in slight decreases in total yields.

Main effects of P sources on yield were also significant. Of the three sources, significantly higher yield was obtained with OSP; yields with DAP and CSP were comparable.

The effect of fertilizer placements on total yield was also significant. Total yields were significantly higher with the broadcast placement than with the band placement.

Mineral Composition of Plant Tissues

The application of increased rate of Cu to soil resulted in increased levels of Cu in the plant tissues at both sampling periods, but decreased tissue P concentration at harvest; Cu rate had no effect on tissue P level at 30 days after planting (Table 30).

The application of increased rates of P increased P levels in the tissues but significantly reduced tissue Cu at both sampling periods.

An interaction between Cu rate and fertilizer placement on tissue Cu levels 30 days after planting was found. The interaction is shown on Table 31. There was no difference in tissue Cu levels between placement at lower Cu application. But at the highest Cu application rate (8.96 kg/ha), tissue Cu level with the broadcast placement was significantly higher than with the band placement.

Greenhouse Experiments

Solution Culture Experiment, 1972

Effects of Cu and P rates on dry matter yield and mineral composition of plant tissues

The effects of Cu rate on dry matter production of cucumber harvested 45 days after seeding were linear and quadratic (Table 32). Without Cu, mean dry matter yield per plant was 4.1 g (Table 33). With an increase in Cu rate from 0 to 0.02 ppm, dry matter yield was increased to 11.2 g. However, a further increase in Cu application to 0.20 ppm resulted in a decrease in dry matter to 9.6 g/plant.

Effects of Cu rates on yield were independent of P effects. The main effect of P on dry matter yield was significant. Plant yield increased with an increase in the P rate from 0 to 60 ppm. However, yield was slightly decreased when P application rate was increased to 120 ppm.

The application of Cu increased Cu but significantly decreased P levels in the plant tissues. The application of P, on the contrary, reduced Cu but raised tissue P concentrations. However, the correlation coefficient between Cu and P in the plant tissues was not significant (Table 34). Symptoms of Cu or P deficiency were not observed.

Solution Culture, 1973

This experiment was similar to the 1972 solution culture experiment except for one major aspect: source of N

Table 32 Analysis of variance of dry matter yield and mineral composition of plant tissues, solution culture experiment, 1972

Source	df	Dry weight	Cu	P	Fe
Blocks	2	12.4226	0.2710	0.05202	793.92
P rates					
Linear	1	2.8909	1.1971	1.76411**	0.08
Quadratic	1	20.3859	0.6061	0.42047**	200.22
Cubic	1	0.5821	0.0012	0.04561	15485.59**
Cu rates					
Linear	1	49.6924**[z]	207.1111**	0.00744	13013.8[illegible]
Quadratic	1	287.7893**	31.3106**	0.18200*	28474.[illegible]
P x Cu					
Lin x Lin	1	1.1682	0.2043	0.00271	79.88
Remainder	5	9.0456	3.2028	0.09465**	4245.31
T(1,3) vs. Others	1	24.6469*[y]	4.4431*	0.96215**	3107.77
Error	24	5.4348	1.3396	0.02118	1747.67

[z]Significant at the 1% level.

[y]Significant at the 5% level.

Table 33. Main effects of P and Cu rates on dry matter yield and mineral composition of plant tissues, solution culture experiment, 1972

Treatment	Dry Weight	Mineral Composition Cu	P	Fe
P rates, ppm	g/plant	ppm	%	ppm
0	5.3	9.1	0.24	73
15	7.3	7.9	0.46	85
30	8.1	8.0	0.77	140
60	9.6	8.0	0.99	93
120	8.2	7.5	1.10	107
F value[z]			L**Q**	C**
Cu rates, ppm				
0	4.1	4.8	0.93	155
0.02	11.2	7.6	0.75	82
0.20	9.6	11.1	0.82	83
F value[z]	L**Q**	L**Q**	Q**	L*Q**

[z]Rate effects were linear (L), quadratic (Q), and cubic (C) at the 5% (*) and 1% (**) levels of significance.

Table 34. Correlations between levels of minerals in the plant tissues in the solution culture experiment, 1972

Elements in the plant tissues	Elements in the plant tissues		
	Cu	P	Fe
	Correlation coefficients		
Cu		-0.0763	$-0.4476*^{z}$
Fe			0.1635

^{z}Significant at the 5% level.

(NH_4^+-N and NO_3^--N) was introduced as a variable factor.

Effects of Cu on dry matter yield

There was a linear increase in dry matter yield with an increase in Cu applications (Table 35). The main effects of Cu rate, P rate and source of N on dry weight and mineral composition and plant tissues are presented in Table 36. At Cu rates of 0, 0.02 and 0.20 ppm, dry weights were 4.4, 4.7 and 4.8 g/pot, respectively.

A Cu -P interaction significantly influenced dry matter weight yields (Table 37). At the lowest P rate, dry weights increased linearly with an increase in the Cu rates from 0 to 0.2 ppm. At the higher P rates, dry weights decreased with similar increase in Cu.

Effects of Cu application on mineral composition of plant tissue

Levels of P, Ca and Fe in the plant foliage were not significantly affected by the rate of Cu applied. However, there was a slight decrease in the concentration of P in the plant tissues with an increase in the Cu rate. Cu and Fe levels on the other hand were slightly increased by increased Cu rate (Table 36).

The effects of Cu application on Mg and K levels were linear and quadratic. The concentrations of K in the tissues were 2.39, 3.21 and 2.31 percent at Cu rates of 0, 0.02 and 0.20 ppm. Mg concentration increased with an in-

Table 35. Analysis of variance of dry weight and mineral composition of plant tissues, solution culture experiment, 1973

Sources of variation	df	Dry weight	Cu	P	Ca	Mg	K	Fe
			Mineral composition of plant tissues					
		Mean squares						
Rep	2	0.165	3.296	0.182	0.546	0.067	0.400*	308.825
N sources	1	213.600**[z]	105.281*	0.011	11.482	0.190	23.115	15,020,000
Error (a)	2	1.100	4.296	0.404	0.439	0.017	0.076	1,169.040
P rates	2	0.175	6.805*	1.082*	0.564*	0.037*	0.270	1,309.28*
Linear	1		12.721**	2.132**	0.218	0.002		2,587.410*
Quadratic	1		0.889	0.032	0.911**	0.070**		31.140
Cu rates	2	0.825	46.470**	0.033	0.188	0.020**	4.445**	91.20
Linear	1		80.40**			0.008	0.056	
Quadratic	1		12.539**			0.031**	8.841**	
Cu rates x P rates	4	1.545*[y]	3.505	0.013	0.065	0.003	0.316	198.060
Lin x Lin	1	3.840**						
Lin x Quad	1	1.6805						
Quad x Quad	1	0.6670						
Others	1	0.0000						
Cu rates x N sources	2	1.590	1.525	0.018	0.236	0.011	0.243	604.88
P rates x N sources	2	1.035	0.099	0.132*	0.186	0.012	0.588	54.14
Lin x Lin	1			0.253**				
Quad x Quad	1			0.012				
Error (b)	36	0.524	1.437	0.158	0.117	0.005	0.195	303.45

[z]Significant at the 1% level.
[y]Significant at the 5% level.

Table 36. Main effects of source of N and P and Cu rates on the dry weight and mineral composition of plant tissues

Treatment	Dry weight	Mineral composition of plant tissues					
		Cu	P	Ca	Mg	K	Fe
N source	g/pot	ppm	%	%	%	%	ppm
NH_4^+	2.6	7.0	0.64	1.69	0.45	4.93	47
NO_3^-	6.5	9.8	0.66	2.61	0.56	2.37	80
F value[y]	**	*				*	
P rates, ppm							
30	4.7	9.1	0.42	2.32	0.54	2.65	73
60	4.5	8.3	0.62	1.97	0.46	2.52	62
120	4.6	7.9	0.91	2.17	0.53	2.74	56
F value[z]		L**	L**	Q**	Q**		L*
Cu rates, ppm							
0	4.4	7.3	0.64	21.0	0.48	2.39	66
0.02	4.7	7.9	0.69	2.25	0.54	3.21	65
0.20	4.8	10.3	0.61	2.11	0.51	2.31	65
F value[z]		Q**			Q**	Q**	

[z]Effects were significant at the 5% (*) and 1% (**) levels

[y]Rate effects were linear (L) and quadratic (Q) at the 5% (*) and 1% (**) levels.

Table 37. Interactions of Cu and P rates on Cu? matter yield, 1973 solution culture[z]

P rates	Cu rates, ppm			Mean
	0	0.02	0.?	
ppm		g/pot		
30	3.87	4.87	5.37	4.70
60	4.68	4.37	4.47	4.50
120	4.50	4.80	4.42	4.57

[z]Linear x linear interaction between Cu and P rates was significant at the 1% level

crease in the rate of Cu applied. At Cu rates of 0, 0.02 and 0.20 ppm, Mg concentration in the plant tissues were 0.48, 0.54 and 0.51 percent, respectively.

The effect of Cu application on dry matter and mineral composition of plant tissues were independent of the source of N applied (Table 35).

Effects of P on dry matter yield and mineral composition of plant tissues

Main effects of P rate on dry matter yield were not significant. The levels of minerals in the plant tissues were, on the other hand, significantly affected by the rate of P applications. As the rate of applied P was increased, Cu, Ca, Mg and Fe concentrations in the tissues were reduced but P and K concentrations were increased (Table 36).

Effects of sources of N on dry matter yield and mineral tissue composition

A significantly higher dry matter yield was obtained from plants grown with NO_3^--N than with NH_4^+-N. Dry weights were 6.5 g/pot with NO_3^--N and 2.6 g/pot with NH_4^+-N (Table 36).

Tissue concentrations of Cu and K were significantly affected by sources of N. Tissues of plants grown with NO_3^--N had higher contents of Cu than those grown with the NH_4^+-N. The effects of sources of N on K were opposite to that of Cu. K concentration in the plant tissues was higher with NH_4^+-N.

Tissue concentrations of P, Mg, Ca and Fe were not significantly affected by the sources of N; concentrations of these elements were slightly lower in plants grown with NH_4^+-N.

Correlations

Dry matter yield was positively correlated with Cu, Ca, Mg and Fe concentrations in the tissues (Table 38); K concentration in the plant tissue was negatively correlated with dry matter yield. There was no correlation between dry matter yield and tissue P levels.

Correlation between the various minerals in the plant tissues are shown in Table 39. Significant correlations were found between Cu and K, and Fe concentrations in the plant tissues; P concentrations correlated significantly with Mg and K.

Soil Culture, 1972

In both soil culture experiments (1972 and 1973), plant growth was variable and vigor was low. Cu deficiency symptoms were not as pronounced as those observed in the field.

Effects of Cu and P rates on dry matter yield and mineral composition of plant tissue

The effect of rate of Cu application on dry matter yield was linear and quadratic (Tables 40 and 41). An increase in Cu rates from 0 to 0.2 ppm increased dry matter

Table 38. Correlation between dry matter yield and concentrations of minerals in the plant tissues, solution culture experiment, 1973

Elements in the plant tissues	Correlation with dry matter yield
	r
Cu	0.6119*[z]
P	-0.0724
Ca	0.7230*
Mg	0.9456*
K	-0.7265*
Fe	0.6599*

[z]Significant at the 5% level.

Table 39. Correlation between Cu, P and other elements in the plant tissues, solution culture experiment, 1973.

Elements in the plant tissues	Elements in the plant tissues				
	P	Ca	Mg	K	Fe
	Correlation coefficients, r				
Cu	-0.1608	0.1704	0.4579	-0.4971*	0.3873*
P		0.1481	0.3129*[z]	0.1245*	-0.1402

[z]Significant at the 5% level.

Table 40. Analysis of variance of dry weights and mineral composition of plant tissues, soil culture experiment, 1972

Sources of variation	df	Dry weight	Cu	P	Fe
Blocks	2	0.9162	4.3760	0.02317	234.07
P rates					
Linear	1	5.6000*	0.0111	7.08683**[z]	3144.71*
Quadratic	1	2.4367	1.3186	0.28961**	1940.65
Cubic	1	0.4624	1.1627	0.02372	652.90
Quartic	1	0.2685	1.2996	0.09151	120.05
Cu rates					
Linear	1	10.3467**	0.3560	0.05681	[illegible]
Quadratic	1	5.3364**	6.3053	0.17648*[y]	[illegible]
P rates x Cu rates					
Linear x Linear	1	1.0238	11.1156*	0.04266	653.00
Remainder	7	1.2755	1.4033	0.04632	392.16
Error	28	0.6388	1.8531	0.03163	671.38

[z]Significant at the 1% level.

[y]Significant at the 5% level.

Table 41 Main effects of P and Cu rates on dry matter yield and mineral composition of plant tissues, soil culture experiment, 1972

Treatment	Dry matter yield, wt/pot	Mineral composition		
		Cu	P	Fe
P rates, ppm	g	ppm	%	ppm
0	2.3	4.7	0.18	60
15	2.4	4.5	0.36	75
30	2.8	4.9	0.71	89
60	2.3	4.1	0.91	87
120	1.4	4.8	1.3	90
F value[z]	L**		L**Q**	L*
Cu rates, ppm				
0	1.5	4.9	0.80	95
0.2	2.4	4.0	0.64	75
2.0	2.9	4.8	0.66	70
F value[z]	L**Q**		Q*	L*

[z]Rate effects were linear (L) and quadratic (Q) at the 5% (*) and 1% (**) levels of significance, respectively.

yield from 1.5 to 2.4 g/pot. A further increase in Cu rate to 2.0 ppm increased dry matter yield from only 2.4 to 2.9 g/pot.

The main effect of P on dry matter yield, however, was significantly quadratic. An increase in yield was obtained with P applications up to 30 ppm. Application rates higher than 30 ppm resulted in yield reductions. Effects of Cu and P were independent.

Tissue Cu concentration was not influenced by soil applications of Cu (Tables 40 and 41), but P and Fe concentrations in the tissues were affected significantly by the rate of Cu applications. Increased rate of Cu applications resulted in decreased concentrations of P and Fe in the plant tissues. On the other hand, P applications had no effect on Cu concentrations in the tissues but significantly affected the levels of tissue P and Fe. Concentrations of P and Fe in the tissues increased with increased rate of P applications.

Soil Culture, 1973

Dry matter yields were not significantly influenced by rate of Cu or P application (Table 42). With P rates of 15, 30, 60, and 120 ppm, dry matter yield were 4.8, 5.4, 5.1, and 5.0 g/pot, respectively; with Cu rates of 0.1 and 2 ppm yields ranged from 4.8 to 5.2 g/pot (Table 43).

Cu in the tissues increased with increased rate of Cu application. This significant effect was both linear and

Table 42. Analysis of variance of dry weights and mineral composition of plant tissues, soil culture experiment, 1973

Sources of variation	df	Dry weight	Mineral composition of plant tissues		
			Cu	P	Fe
			Mean squares		
Blocks	3	1.5547	1.7072	0.4847	4,060.52
P rates	3	0.8570	1.0905	0.3417*[x]	1,472.55
Linear	1			0.8857**[y]	
Quadratic	1			0.0425	
Cubic	1			0.0963	
Cu rates	2	0.6850	11.2229*	0.1288	3,579.30**
Linear	1		18.6606**		5,012.51**
Quadratic	1		3.8400		2,146.10
Cu rates x P rates	6	0.2351	0.5490	0.0308	684.34
Error	33	0.3839	0.5743	0.0828	867.89

[x]Significant at the 5% level.

[y]Significant at the 1% level.

Table 43 Main effects of P and Cu rates on dry matter yield and mineral composition of [illegible] 1973 soil culture experiment

Treatment	Dry matter yield	Mineral composition Cu	P	Fe
P rates, ppm	g/pot	ppm	%	ppm
15	4.8	3.5	0.41	62
30	5.4	3.7	0.67	84
60	5.1	4.2	0.72	86
120	5.0	3.6	0.80	83
F value[z]			L**	
Cu rates, ppm				
0	4.8	2.8	0.55	61
1	5.2	4.1	0.71	88
2	5.2	4.3	0.69	86
F value[z]		L**Q**		L**

[z]Rate effects were linear (L) and quadratic (Q) at the 5% (*) and 1% (**) levels of significance.

quadratic. Rate of Cu application, however, had no effect on tissue P levels but it significantly affected Fe concentrations in the tissue. Tissue Fe was increased by increased rate of Cu applications (Table 43). The concentration of P in the plant tissue increased linearly with increased rates of P application.

DISCUSSION

The results of the 1971 and 1972 experiments pertaining to the influence of Cu rates on cucumber yields were consistent. In both years the application of Cu at various rates resulted in increased early and total yields. Low yields and in some cases death of the young growing seedlings were the results when Cu was not applied or applied in low amounts. Total yields were increased approximately 400 percent in the 1971 experiment and approximately 100 percent in the 1972 field experiment with the application of increased rates of Cu. Significant increases in dry matter yields due to Cu applications were also observed in two of the greenhouse experiments. A positive response to Cu application was also noted on the concentrations of Cu in the plant tissues. Increased rate of Cu applications resulted in a significant increase in the concentrations of Cu in the plant tissues in the field and greenhouse experiments.

The response of cucumber to Cu applications can be accounted for in part by the low level of available Cu in the soil. The soil used in the present study was analyzed for Cu, using 0.1N HCl as extractant, and was found to contain approximately 1 ppm of extractable Cu. A number of investigations pertaining to Cu fertilization of watermelons had been conducted on areas with soil similar to the one

used in the present study. Results of such studies have shown high yield responses of watermelons to Cu applications (55, 56, 57, 58).

Cucumbers responded very well to Cu applications. Maximum yield was obtained at the highest level of Cu considered in the study (8.96 kg/ha). Tissue Cu levels were positively correlated with yields. However, the level of Cu in the plant tissues was not a good basis to determine the plant requirement for Cu. Tissue Cu concentration varied considerably at different stages of growth and from one season to another. In 1971, Cu deficiency symptoms were frequently observed with plants having tissue Cu concentration of approximately 3.2 ppm at the harvest stage. In 1972 season, 2.7 ppm Cu in the tissue appeared to be an adequate level.

It had been previously reported on watermelons that high rate of P applications might result in the reduction of yields due to an induced Cu deficiency. Everett et al (25) found that watermelon yields were significantly affected by an interaction between Cu and P. The addition of one of these elements without the other resulted in no significant increase in yield. Yield was highest with the addition of both elements. Locascio et al. (57) reported that the application of high P rate increased the concentrations of P in the watermelon tissues but decreased tissue Cu. They also reported that without the addition of Cu, high P applications resulted in a yield reduction.

Results similar to those mentioned above were obtained in the two field and solution culture experiments in the present study. In the 1971 experiment, the interaction between Cu and P was not significant, nevertheless, there were clear indications, especially at high rates of Cu, that P reduced an apparent Cu toxicity. In the 1972 experiment, the interaction between Cu and P yields was significant. Yields were lower when either of the elements was applied in very low amounts. However, yield was highest when both elements were present in optimum amounts. Depression in Cu uptake with increased applications of P was observed in the solution culture experiments. At high levels of applied P, Cu concentrations in the tissues were reduced in both solution-culture experiments. But in the two soil-culture experiments, there was no indication that Cu concentration in the plant tissues was depressed even at P application rate as high as 120 ppm.

Previous workers attributed the inducement of Cu deficiency by high rates of P application to fixation of available Cu by P (44). Later workers (32) indicated that the depression of Cu availability by high rates of P application may be related to a reduced solubility of Cu as a result of P coating around copper sulfate crystals. This explanation of depression of Cu availability involved either physical or chemical reaction between Cu and P. Dekock et al. (22) suggested a different explanation for Cu-P interaction. They stated that P application did not

depress Cu availability but the increased growth and the increased demand for Cu resulted in Cu deficiency. Where Cu was in limited supply in the soil, the application of high rates of P could enhance the deficiency of Cu. Present investigations may support the latter explanation of Cu-P relation because of the lack of consistency in the occurrence of the interaction. In the present study consisting of six experiments, the interaction between Cu and P was significant only in one experiment (1972 field experiment). In the two soil culture experiments high rates of P application did not depress or even show any tendency that it depressed Cu availability to plants. In a previous study, Bingham (12) also failed to induce significant depression of Cu availability by the application of P. The fact that high rate of P application did not invariably result in the depression of Cu availability or uptake made it more attractive to suppose that the Cu-P interaction was more of a biological response rather than a physical or chemical type reaction. Moreover, the application of other elements to plants which result in the enhancement of growth could also induce Cu deficiency. For instance, Labanauskas et al.(52) reported that heavy application of N significantly reduced Cu and B contents of avocado leaves.

In the present study, application of high amounts of Cu also resulted in slight reductions in tissue P. Cain (17) pointed out that decrease in the leaf tissue concentration of an element does not represent decreased absorption

but such decrease may be due to a growth dilution effect and to changes in the distribution of such an element within the plant. He added further that one kind of ion has little if any direct effect upon the total absorption of another ion by the plant. The percentage composition of one ion may be decreased by the application of another if its rate of absorption does not keep pace with the rate of growth stimulated by the added ion.

Data in the present study further indicated that the interaction between Cu and P was not a soil-mediated reaction. The apparent depression in the tissue Cu concentration due to high P rate was noted even among plants growing in nutrient solution.

Excessive P application may not only enhance deficiency of other limiting elements but P at excessive rates may have toxic effects (36). Apparent toxicity of P at high rates was also observed in this study. P rates higher than 28 kg/ha resulted in decreased yields.

Of the three P sources considered in the present study (OSP, DAP and CSP), highest yields were obtained with OSP, and the lowest yields, with CSP and DAP. These results agreed with the results obtained by previous workers (57).

OSP probably contains more impurities than such fertilizer materials as DAP and CSP (87). Such impurities became critical when the limiting element(s) in the soil are among those found as impurities. It is quite possible that the

better yield and growth performance of plants grown with the CSP was due to the impurities present in the fertilizer.

From a statistical viewpoint, CSP and DAP were comparable but there were indications that diammonium phosphate was the poorest source of P (Table 30). The poor performance of watermelon plants with diammonium phosphate was attributed by Locascio et al. (57) to a possible reduction in Cu availability due to increased pH resulting from the application of diammonium phosphate. Data on tissue analyses of cucumber in the present study did not indicate, however, that Cu availability was depressed more with the application of DAP than with CSP. For this reason, it is probable that process or processes other than depression of Cu availability could have brought about a yield reduction greater than those grown with concentrated superphosphate.

In the greenhouse experiments with nutrient solutions, the sensitivity of cucumber plants to NH_4^+-N was demonstrated. Plants grown with NH_4^+-N produced much lower dry matter yield than those grown with NO_3^--N. The sensitivity of some plants to NH_4^+-N had been previously reported (60, 63). Vines and Wedding (86) reported a mechanism for ammonium toxicity. They believed that gaseous and undissociated aqua ammonia in equal concentrations tended to inhibit respiration. It is possible, therefore, that, with DAP as the source of P the NH_4^+-N could adversely affect NH_4^+-sensitive plants especially under conditions of low nitrification.

Results of the 1971 and 1972 field experiments gave

sufficient evidence that broadcast placement was a more efficient method of applying P and Cu fertilizers for cucumber plants. In both years, yields obtained with the broadcast placement were higher than with the band placement. There was a yield difference of as much as 80 percent between placements.

In both years there were significant interactions between Cu rates and fertilizer placement. The interactions were probably related to the phytotoxicity of Cu at the higher Cu rates. This property of Cu as a nutrient, makes fertilizer placement a very important factor especially at high rates of Cu application (59).

SUMMARY

This study was conducted to determine the following: (1) the effects of Cu rates on cucumber production, (2) the effects of P rates and sources and fertilizer placements on cucumbers, and (3) to study the relationship between Cu and P.

Two similar field experiments were conducted during 1971 and 1972, and four greenhouse experiments during 1972 and 1973. The treatments in the field experiments were 80 factorial combinations of three P sources (OSP, DAP and CSP), four P rates (0,28, 56 and 112 kg/ha), four Cu rates (0, 2.24, 4.48 and 8.96 kg/ha), and two fertilizer placements (band and broadcast) In the greenhouse, two of the experiments were conducted with potted soil and two experiments with nutrient solutions. With the first soil experiment, treatments were factorial combinations of three Cu rates (0, 0 02 and 2 ppm) and five P rates 0, 15, 30, 60 and 120 ppm). In the second experiment with soil, treatments were combinations of three Cu rates, 0, 1 and 2 ppm and four P rates, 15, 30, 60 and 120 ppm. In the first solution culture experiment, treatments consisted of factorial combinations of three Cu rates, 0, 0,02 and 0.2 ppm, and five P rates, 0 15, 30, 60 and 120 ppm In the

second nutrient solution experiment, P rates were 30, 60 and 120 ppm and Cu rates were 0, 0.02 and 0.2 ppm. In addition to Cu and P rates, source of N (NH_4^+ and NO_3^-) was also varied in the second solution culture experiment. In all greenhouse experiments, the source of Cu was copper sulfate (25.4% Cu). The P was obtained equally from mono- and disodium phosphate. In all experiments, 'Poinsett' cultivar of cucumber was used as the test plants.

Results of the field experiments showed that cucumber yields increased significantly with increased rates of Cu application. The large increases in yield was obtained with an increase in the rate of Cu applications from 0 to 2.24 kg/ha. Applications higher than 2.24 kg/ha of Cu resulted in only slight but significant increases in yield. Increased applications of P from 0 to 28 kg/ha also resulted in large increases in yield but applications beyond 28 kg/ha slightly decreased cucumber yields.

Pooled analysis of the two-year data showed an interaction between P and Cu rates for early yields. At low Cu application rates, yields were reduced with increases in the rate of applied P. Yield was highest, however, when both elements were applied in higher amounts. A similar relationship between applied Cu and P rates seemed to exist for the total yields.

Yields were significantly affected by P sources and fertilizer placements. Highest yield was obtained from plants fertilized with P from OSP. The broadcast fertilizer

placement was superior to band applications. However, fertilizer placement interacted with Cu rate effects. Increases in yield with increased rates of applied Cu were greater with broadcast placement than with band placement.

Significant effects of P and Cu applications were observed on the mineral composition of plant tissues. Tissue Cu levels increased with soil Cu application but decreased with increased P applications. Tissue-P levels increased a 100% with increased P applications but were only slightly affected by Cu rates.

A positive correlation between yield and tissue Cu concentration was found. P concentration in the tissues, however, was found to be correlated negatively with yields. Significant correlations between tissue P and tissue Cu concentrations were negative.

In general, results of the greenhouse experiments pertaining to the effects of Cu and P rates on dry matter yields and mineral composition of plant tissues agreed with those of the field experiments. In the soil experiments, dry matter yields increased as Cu application rates increased from 0 to 1 ppm. Similarly, the application of P at 30 ppm resulted in increased yields. Higher P rates decreased dry matter yields. In the water-culture experiments, optimum levels of Cu and P were found to be approximately 0 02 and 30 ppm, respectively

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He is married to the former Leonila D. Francisco and is now the proud father of two young girls, Rowena and Lennie.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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